



# Project Summary

## Evaluation of Rotary Kiln Incinerator Operation at Low-to- Moderate Temperature Conditions

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A 12-test program was performed at the Environmental Protection Agency's Incineration Research Facility to study the effectiveness of incineration at low-to-moderate temperatures in decontaminating soils containing organic compounds with different volatilities (boiling points). Test parameters were soil moisture content, treatment temperature, treatment time, soil bed depth, and degree of soil agitation. A related objective was to determine the fate of contaminant metals in the contaminated soil under these conditions.

The data demonstrate that compound volatility and treatment temperature are the key parameters that will affect whether a contaminated soil can be successfully decontaminated. Low-boiling (volatile) compounds can be rapidly (in less than 20 minutes) driven out of the soil nearly quantitatively to non-detectable levels at a 316°C (600°F) kiln exit gas temperature. High-boiling compounds require higher treatment temperatures (greater than 482°C [900°F] kiln exit gas temperature) and longer treatment times (longer than 30 minutes) in order for more than 99.9% of the compounds to be driven out.

Increased soil temperature favors decontamination and is essential for satisfactory decontamination of high-boiling compounds. However, while soil temperature is important, other parameters, such as the presence of moisture or the degree of agitation, can affect the decontamination process and can be beneficial under the right combination of conditions.

The effects of moisture on decontamination effectiveness are manifold. Increased moisture reduces soil heat-up rates and thus tends to slow down the decontamination process. Test data suggest that increased moisture, for some materials, may increase soil agitation at moderate-to-high kiln rotation speeds. This, in turn, can lead to faster heat absorption and reduced mass transfer resistance, but shorter soil residence time. Faster heat absorption and reduced mass transfer resistance increases decontamination rate. Shorter residence time lowers the extent of organic constituent decontamination, if the decontamination rate for that constituent is slow. In addition, increased moisture may enhance decontamination of the less-volatile organic compounds through steam stripping, provided that the additional moisture does not prevent the soil from reaching necessary temperatures.

With the exception of mercury, the extent of metal volatilization from the treated soil was not significantly affected by any of the test variables. Mercury was volatile, tending to be equally distributed between the kiln ash and the scrubber exit flue gas. At the highest kiln exit gas temperature of 649°C (1,200°F), the extent of mercury volatilization increased with treatment time.

The effects of thermal treatment on metals leachability in the toxicity characteristic leaching procedure vary from metal to metal. Among the test variables, the most influential is treatment temperature. Lead and barium leachabilities

were not affected by any of the test variables. Leachable fractions of arsenic and cadmium decreased when soil temperature increased. In contrast, leachable fractions of chromium and mercury increased when soil temperature increased.

*This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate two-volume report of the same title (see Project Report ordering information at back).*

## Introduction

As part of the EPA's efforts to remediate Superfund sites, several remediation technologies can be candidates for consideration. One of the more frequently used technologies to decontaminate soils contaminated with organic hazardous constituents is incineration. High-temperature incineration, while effective in destroying organic compounds, may not be necessary for some soils that need treatment, such as soils contaminated with volatile organic compounds (VOCs). Also, in soils contaminated with toxic trace metals, high-temperature incineration may increase the volatilization of some metals into the combustion flue gas. The presence of elevated levels of volatile trace metals in the flue

gas can pose increased challenges to an air pollution control system (APCS).

Another thermal treatment technology, thermal desorption, may be an attractive alternative to incineration. When successful in decontaminating soils to the necessary degree, thermal desorption treatment of soils offers the benefits of lower fuel consumption, avoidance of slag formation, reduced metals volatilization, and reduced APCS demands.

Most conventional rotary kiln incinerators can be easily operated at temperatures below those typically employed for incineration treatment. Thus, the question arises: how effective is the treatment of contaminated soils by a rotary kiln incinerator operated at the low-to-moderate temperatures?

To address this question, a series of tests was conducted in the rotary kiln incineration system (RKS) at EPA's Incineration Research Facility (IRF). In these tests the kiln of the RKS operated at low-to-moderate temperatures. The test program consisted of 12 tests under 11 different kiln operating conditions; one test condition was tested in duplicate.

The objective of the test program was to study the global effects of five parameters believed to be of primary importance in the effectiveness of soil decontamination and in the fate of contaminant metals. These parameters were soil mois-

ture content, treatment temperature, treatment time, solids bed depth, and degree of solids agitation.

The results obtained from the test program were intended to yield the following information:

- The relationship between compound boiling point (vapor pressure) and the extent of decontamination for each organic contaminant
- How the solids bed temperature affects decontamination
- How the presence and the amount of moisture affect organic decontamination effectiveness
- The relationship between treatment time, treatment temperature, and organic constituent decontamination effectiveness
- The distribution of trace metals in process discharges when a metal-contaminated soil is treated by thermal desorption
- Whether thermal desorption treatment conditions affect a metal's leachability from the treated soil

## Test Program

### Test Facility

All tests were performed in the RKS at the IRF. A process schematic of the RKS

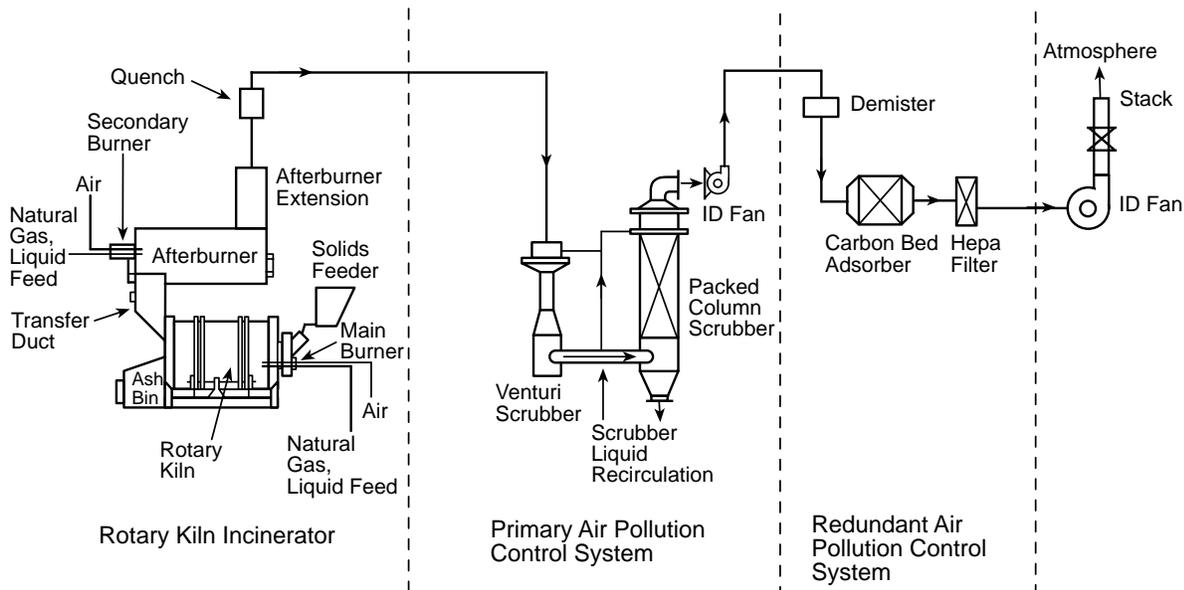


Figure 1. Schematic of the IRF rotary kiln incineration system.

is shown in Figure 1. The IRF RKS consists of a primary combustion chamber, a transition section, and a fired afterburner chamber. After exiting the afterburner, flue gas flows through a quench section followed by a primary APCS. The primary APCS for these tests consisted of a venturi scrubber followed by a packed-column scrubber. Downstream of the primary APCS, a backup secondary APCS, composed of a demister, an activated-carbon adsorber, and a high-efficiency particulate air (HEPA) filter is in place.

### **Test Contaminated Soil**

A synthetic contaminated soil was prepared for testing by mixing a locally obtained topsoil with an attapulgite clay oil sorbent in a 1:1 weight ratio. This clay additive was required to allow the test mixture to be reliably fed continuously to the kiln of the RKS using a screw feeder. The local topsoil without the clay additive readily bridged in the feed hopper, preventing reliable feed.

The test soil/clay mixture was spiked to contain contaminants reflecting contamination by gasoline, volatile organic solvents, semivolatile organic compounds associated with coal tar, and trace metals. Benzene, n-heptane, and n-octane represented gasoline components; benzene, toluene, tetrachloroethene, and chlorobenzene represented volatile organic solvents; and naphthalene, phenanthrene, and pyrene represented coal tar constituents. Spiking levels ranged from 2,000 to 4,800 mg/kg in the final synthetic contaminated soil mixture for the volatile organic compounds (VOCs) added, and from 200 to 600 mg/kg for the semivolatile organic compounds (SVOCs) added. The test soil/clay mixture was also spiked to contain commonly encountered hazardous constituent trace metal contaminants. The trace metals spiked were arsenic, barium, cadmium, chromium, lead, and mercury. Spiking levels ranged from 10 to 200 mg/kg in the final synthetic contaminated soil mixture.

The soil/clay mixtures were prepared in two 3.5-ft<sup>3</sup> (100-L) cement mixers via the addition of weighed quantities of each mixture component into a mixer. The organic contaminants were added to the soil/clay mixtures as a combined organic solution. Trace metal contaminants were added in an aqueous solution. After spiking, the moisture content of the spiked/soil/clay mixture was adjusted to one of two test program targets of 10% or 20% by adding additional water, if needed. The final soil mixtures were tumbled to uniform appearance, then transferred to 55-gal (208-L)

drums that were then sealed. Contaminated soil mixtures were allowed to age between 7 and 14 days before use in a test.

Table 1 summarizes the organic solution composition used to spike the test mixtures. The organic contaminant mixture was added to the soil/clay mixtures in the ratio of 0.02 kg organic liquid per kg final soil mixture. Resulting contaminated soil organic constituent concentrations are also noted in Table 1. The composition of the concentrated aqueous solution of trace metals added is summarized in Table 2. All metal constituents were added as soluble nitrate salts except arsenic, which was added as As<sub>2</sub>O<sub>3</sub> dissolved into the acid nitrate spike solution. The metals spike solution was added to the soil/clay mixtures in the ratio of 0.05 kg spike solution per kg of final contaminated soil mixture. Resulting contaminated soil trace metal concentrations, neglecting native soil/clay metal concentrations, are also noted in Table 2.

### **Test Conditions**

As noted above, the test program consisted of 12 tests under 11 different combinations of the test variables, with one test performed in duplicate. The test parameters were soil moisture content, treatment temperature, treatment time, solids bed depth, and degree of solids agitation. Soil moisture content was directly varied, at 10 and 20%, as noted above. Changes in the other test parameters were caused by changing the RKS operating conditions. The operating conditions varied from test condition to test condition were kiln exit gas temperature, contaminated soil feed rate, and kiln rotation rate. Three target kiln exit gas temperatures were tested, 320°, 480°, and 650°C (600°, 900°, and 1,200°F). Two target feed rates were tested, 70 and 210 kg/hr (150 and 470 lb/hr). Three target kiln rotation rates were tested, 0.2, 0.5, and 1.5 rpm.

Kiln exit gas temperature primarily affected peak solids bed temperature. Peak solids bed temperatures corresponding to the above kiln exit gas temperatures were about 120°, 260°, and 430°C (250°, 500°, and 800°F), respectively. Kiln rotation rate affected both degree of agitation and soil residence time in the kiln, or maximum treatment time. Total kiln soil residence times corresponding to the above rotation rates were 60, 40, and 30 minutes, respectively. The combination of feed rate and kiln rotation rate affected solids bed depth.

Total treatment times were changed by varying kiln rotation rates, as noted above.

However, to allow for the evaluation of treatment effectiveness at partial treatment times for each test condition, samples of the soil bed material were taken at four axial locations along the kiln for each test, in addition to a soil discharge sample. These additional samples corresponded to four different treatment times at each test condition.

A summary of the target test operating conditions and soil moisture contents for each of the specified 12 tests is given in Table 3. The "center point" of the test matrix is represented by Test 2, with soil feed rate at 70 kg/hr (150 lb/hr), kiln exit gas temperature of 480°C (900°F), kiln rotation rate of 0.2 rpm, and soil moisture content of 10%. This test condition was tested in duplicate (Test 12). From this "center point," kiln temperature was varied (Tests 1 and 3), soil moisture content was varied (Test 5), kiln rotation rate was varied (Test 7), and soil feed rate was varied (Test 10). Additional test combinations were performed for the high moisture soil at the base feed rate and rotation rate (Tests 4 and 6), at the high feed rate and base rotation rate (Test 11), and at the base feed rate and increased rotation rate (Test 8). The highest rotation rate was tested at high feed rate with the high moisture soil (Test 9).

For all tests, the afterburner was operated at 1,090°C (2,000°F) to ensure satisfactory burnout of all volatilized organic compounds. The scrubber system was operated under its nominal design conditions to achieve typical scrubber performance. The scrubber was operated at near total recycle, so there was minimum blowdown. The synthetic contaminated soil was fed continuously until all flue gas sampling was completed. Treated soil was continuously removed from the kiln ash hopper via an ash auger transfer system, and deposited in clean 55-gal (208-L) drums. After the completion of each test (all flue gas sampling completed) the system continued to operate at the specified test conditions, without soil feed, until all treated soil was cleared from the kiln. The weight of treated soil collected was monitored continuously throughout the test; the resulting data allowed the calculation of total kiln soil residence times.

A summary of the actual test conditions in effect for each test is given in Table 4. As shown, average kiln exit gas temperature targets were closely met for all tests. Soil bed temperatures were measured at four locations along the kiln axis: 0.6, 1.1, 1.5, and 2.0 m (2.0, 3.5, 5.0, and 6.5 ft) from the kiln feed face. Measurements were made with a specially fabricated

**Table 1. Organic Constituents in the Synthetic Contaminated Soil**

Compound	Molecular weight	Specific gravity	Melting point, °C	Boiling point, °C	Organic liquid mixture composition, wt %	Concentration in soil at an organic liquid fraction of 2%, mg/kg
Benzene	78.1	0.88	6	80	15	3,000
<i>n</i> -Heptane	100.2	0.68	-91	98	15	3,000
Toluene	92.7	0.87	-95	111	15	3,000
Tetrachloroethene	165.9	1.62	-22	121	24	4,800
<i>n</i> -Octane	114.2	0.70	-57	126	15	3,000
Chlorobenzene	112.6	1.11	50	132	10	2,000
Naphthalene	128.2	1.16	80	218	3	600
Phenathrene	178.2	1.18	100	340	2	400
Pyrene	202.2	1.27	156	404	1	200

**Table 2. Trace Metal Constituents in the Synthetic Contaminated Soil**

Metal	Aqueous spike solution		Resulting soil feed metal concentration <sup>b</sup> , mg/kg
	Metal concentration, l g/L	Compound concentration <sup>a</sup> , g/L	
Arsenic	0.50	As <sub>2</sub> O <sub>3</sub>	25
Barium	4.0	Ba(NO <sub>3</sub> ) <sub>2</sub>	200
Cadmium	0.20	Cd(NO <sub>3</sub> ) <sub>2</sub> • 4H <sub>2</sub> O	10
Chromium	0.50	Cr(NO <sub>3</sub> ) <sub>3</sub> • 9H <sub>2</sub> O	25
Lead	0.80	Pb(NO <sub>3</sub> ) <sub>2</sub>	40
Mercury	0.20	Hg(NO <sub>3</sub> ) <sub>2</sub>	10

<sup>a</sup>Sufficient HNO<sub>3</sub> added to maintain lead arsenate compounds in solution.

<sup>b</sup>Negligible soil metal concentrations and a ratio of 0.05 kg of spike solution per kg of organic/soil/spike solution mixture assumed.

probe that allowed the immersing of four thermocouples in the soil bed at the respective axial locations. Soil bed temperatures measured for the tests are also given in Table 4.

### Sampling and Analysis

For all tests, the sampling protocol consisted of

- Obtaining a composite sample of the contaminated soil feed material mixture
- Obtaining composite samples of the treated soil in the kiln chamber at four axial locations corresponding to the solids bed temperature measurements: 0.6, 1.1, 1.5, and 2.0 m (2.0, 3.5, 5.5, and 6.5 ft) from the kiln feed face
- Obtaining a composite sample of the treated soil discharge from the discharge collection drum
- Obtaining composite pretest and posttest scrubber liquor samples
- Sampling flue gas for trace metals using an EPA multiple metals train at the venturi/packed-column scrubber exit

- Sampling flue gas for mercury using a Method 101A train at the venturi/packed-column scrubber exit
- Continuously monitoring O<sub>2</sub>, CO, and total unburned hydrocarbon (TUHC) levels in the kiln exit flue gas
- Continuously monitoring O<sub>2</sub> in the afterburner exit flue gas
- Continuously monitoring O<sub>2</sub> and CO<sub>2</sub> downstream of the venturi/packed-column scrubber
- Continuously monitoring O<sub>2</sub> and CO in the stack downstream of the secondary APCS (carbon bed/HEPA filter)
- Sampling the stack gas for particulate, and HCl and Cl<sub>2</sub> using Method 50

As noted above, contaminated soil feed was prepared, placed into 55-gal (208-L) drums, and allowed to age between 7 and 14 days prior to use in a test. Just prior to a test, the drums of soil were opened and sampled. Drum contents were then transferred to the screw feeder hopper for feeding.

Four composite kiln solids bed samples were also collected for each test. One sample was collected using a custom-fabricated quartz scoop at each of the four axial locations where soil bed temperature was measured. Each of these samples represented a different treatment time under the set of other test conditions established for each test. A sample of the final treated soil discharge was also collected from the discharge collection drum after the completion of each test.

Test program samples were analyzed as follows. Unspiked soil/clay absorbent mixture, each test's feed mixture, and all treated soil samples were analyzed for the spiked VOC and SVOC contaminants and the spiked trace metals. A composite of the Test 1, 2, and 3 soil feed, and the final treated soil discharge samples for each of these tests, were analyzed for polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/PCDFs) by Method 8290.

Toxicity characteristic leaching procedure (TCLP) leachates of two composite soil feed samples and of all treated soil samples were prepared and analyzed for the test trace metals. Specifically, leachates were digested by EPA Method

**Table 3. Target Test Conditions**

Test	Kiln exit gas temperature, °C (°F)	Expected peak solids bed temperature, °C (°F)	Kiln rotation rate, rpm	Soil feed rate, kg/hr (lb/hr)	Soil moisture content, %
1.	320 (600)	120 (250)	0.2	70 (150)	10
2.	480 (900)	270 (520)	0.2	70 (150)	10
3.	650 (1,200)	430 (800)	0.2	70 (150)	10
4.	320 (600)	120 (250)	0.2	70 (150)	20
5.	480 (900)	270 (520)	0.2	70 (150)	20
6.	650 (1,200)	430 (800)	0.2	70 (150)	20
7.	480 (900)	270 (520)	0.5	70 (150)	10
8.	480 (900)	270 (520)	0.5	70 (150)	20
9.	480 (900)	270 (520)	1.5	70 (150)	20
10.	480 (900)	270 (520)	0.2	210 (470)	10
11.	480 (900)	270 (520)	0.2	210 (470)	20
12.	480 (900)	270 (520)	0.2	70 (150)	10

**Table 4. Actual Test Operating Conditions**

Test Date	1 1/29/93	2 2/2/93	3 2/4/93	4 1/27/93	5 12/4/92	6 12/16/92	7 1/6/93	8 12/9/92	9 2/11/93	10 1/15/93	11 1/19/93	12 1/21/93
Average soil feed rate, kg/hr (lb/hr)	67 (148)	68 (150)	66 (145)	68 (149)	63 (138)	70 (155)	65 (144)	69 (152)	66 (145)	230 (506)	225 (497)	66 (146)
Kiln exit gas temperature												
Range, °C (°F)	305-331 (501-627)	474-492 (885-918)	641-658 (1,185-1,216)	301-330 (524-626)	463-499 (866-930)	633-660 (1,171-1,220)	471-494 (880-921)	467-501 (873-935)	471-492 (880-918)	287-508 (548-946)	464-500 (867-932)	471-493 (879-919)
Average, °C (°F)	317 (603)	482 (900)	648 (1,199)	316 (601)	482 (900)	648 (1,199)	482 (900)	480 (896)	482 (900)	481 (897)	482 (900)	482 (900)
Kiln rotation rate, rpm	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.5	1.5	0.2	0.2	0.2
Total kiln soil residence time, min	58	68	72	64	61 <sup>a</sup>	56	60	32	27	46	38	64
Average soil bed temperature at "x" m ("x" ft) from feed face, C° (F°)												
0.6 (2.0)	86 (186)	123 (253)	267 (512)	69 (156)	113 (235)	122 (251)	144 (292)	179 (355)	172 (341)	130 (266)	107 (224)	144 (291)
1.1 (3.5)	109 (228)	182 (359)	393 (740)	88 (191)	204 (399)	319 (606)	204 (400)	215 (419)	194 (382)	161 (321)	132 (269)	211 (412)
1.5 (5.0)	115 (239)	228 (443)	434 (814)	98 (208)	260 (500)	401 (753)	249 (481)	239 (462)	245 (473)	175 (347)	149 (300)	257 (495)
2.0 (6.5)	123 (254)	227 (440)	451 (844)	123 (254)	182 (359)	356 (672)	241 (465)	231 (448)	277 (531)	253 (487)	239 (463)	244 (471)

<sup>a</sup>Estimated.

3010 and analyzed for barium, cadmium, chromium, and lead by inductively coupled argon plasma (ICAP) spectroscopy by Method 6010; leachates were digested and analyzed for arsenic by Method 7060; and leachates were digested and analyzed for mercury by Method 7470.

All pretest and posttest scrubber liquor samples were analyzed for the test trace metals by the same methods employed for the TCLP leachate samples. In addition, one composite pretest scrubber liquor and all posttest scrubber liquor samples were analyzed for the spiked volatile and semivolatile organic soil contaminants.

Finally, all multiple metals train samples were analyzed for the non-mercury test trace metals, and the Method 101A sampling train samples were analyzed for mercury.

## Test Results

The following summarizes major test program findings. The test program results and conclusions are summarized according to the points noted in the introduction.

### **Organic Decontamination and Compound Boiling Point**

The test program data clearly demonstrate that lower-boiling compounds (more volatile) can be driven out of the test soil nearly quantitatively (to non-detectable levels) and rapidly (in less than 20 minutes). In contrast, higher-boiling-point compounds remain in the soil, and require higher treatment temperatures (greater than 480°C (900°F) kiln exit gas temperature) and longer treatment times (longer than 30 minutes) for effective soil decontamination. Treatment at gas temperatures less than 480°C (900°F) can result in very poor decontamination of the high-boiling-point organic compounds tested.

### **Organic Decontamination and Soil Temperature**

The test program data demonstrate that elevated soil temperature favors decontamination. In particular, elevated temperature is essential for satisfactory decontamination of high-boiling-point compounds. However, while soil temperature appears to be correlatable to the degree of organic decontamination, it is not, by itself, a sufficient predictive indicator of decontamination level. Other parameters, such as the presence of moisture or the degree of soil bed agitation, can enhance the decontamination process under the right combination of conditions.

### **Organic Decontamination and Soil Moisture Content**

The test program data obtained are difficult to interpret with respect to evaluating the effects of soil moisture content on organic compound decontamination effectiveness. Competing phenomena are likely involved. Three possible explanations for the test observations are developed as follows:

Increases in moisture content reduce solid heat-up rates due to the higher thermal mass (specific heat and latent heat of vaporization). This tends to reduce the rate of organic compound decontamination.

Inferences based on kiln soil holdup weights and kiln soil residence times suggest that increased moisture in the test soils within the tested range increased the soil bed agitation when the kiln was rotated at 0.5 rpm or faster. This increase in agitation led to faster heat absorption and reduced mass transfer resistance, but shorter solids residence times. Faster heat absorption increases the driving force for volatilization. Reduced mass transfer resistance increases decontamination rate. Shorter residence times lower the achievable decontamination extent of an organic constituent, if the decontamination rate for that constituent is slow.

Increased moisture content may enhance the decontamination rates for the less volatile organic compounds through steam stripping, provided that the additional moisture, with its higher specific heat and latent heat of vaporization, does not prevent the soil from reaching temperatures that are necessary for effective stripping of the volatile organic contaminants.

### **Organic Decontamination and Treatment Time and Temperature**

The extent of organic compound decontamination increases with solids residence time and also increases with treatment temperature. However, the relationship between these variables is not straightforward. An attempt to summarize all the test program data is illustrated in Figures 2 and 3. The figures include all test program data collected in the range of treatment times from 7 to 67 minutes, with the difference between soil bed temperature and compound boiling points ranging from -333° to +371°C (-599° to +668°F).

Figure 2 includes 432 data points (4 locations per test, 9 compounds per test and a total of 12 tests for the test program) and is a plot of the extent of decontamination achieved versus the difference

between soil temperature and compound boiling point. The extent of decontamination achieved is represented by the expression  $C/C_o$ , where  $C$  is the final contaminant concentration in the treated soil and  $C_o$  is the feed soil contaminant concentration. The difference between soil temperature and compound boiling point is represented by  $(T_{soil} - T_{b.p.})$  where  $T_{soil}$  is the soil bed temperature and  $T_{b.p.}$  is the compound boiling point.

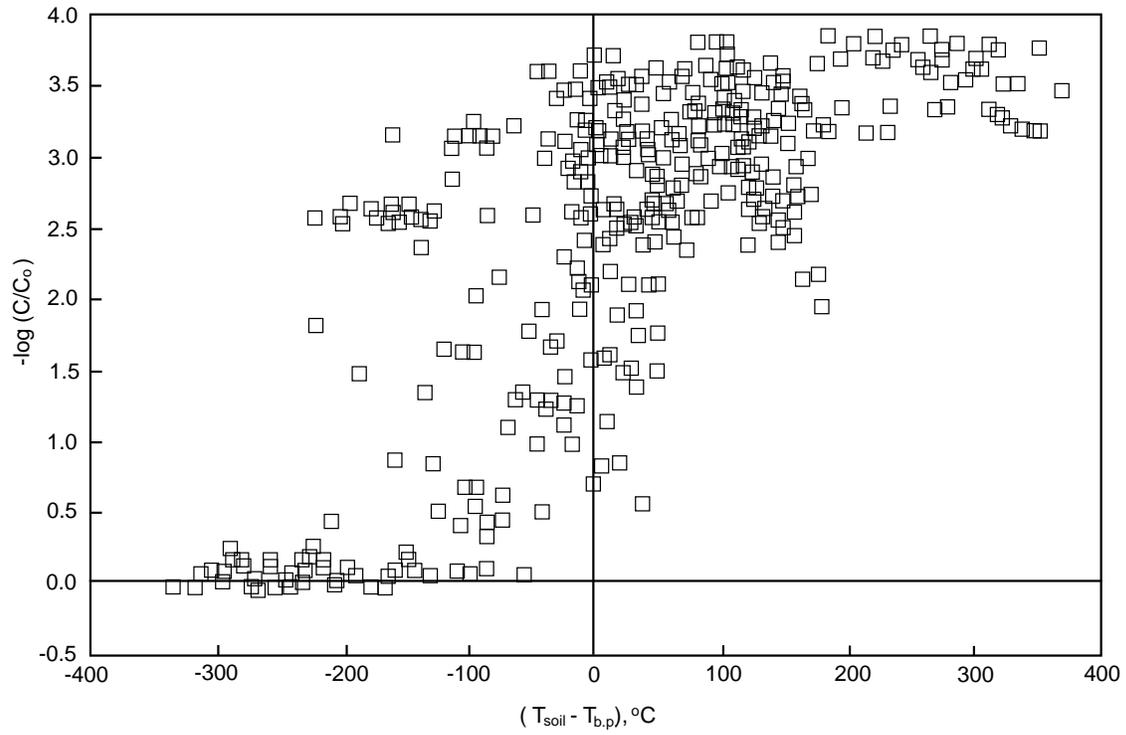
While the data form a definite pattern showing increased decontamination with increased soil bed temperature, the scatter in the test data is significant, thereby indicating some influence by parameters other than treatment temperature.

Figure 3 is an attempt to show the combined effects of soil bed temperature and treatment time, where a first-order dependence on each of the two variables is assumed. In this figure, the horizontal axis is the product of treatment time with the difference between treatment temperature and compound boiling point. This product, with unit of °C-min can be considered the cumulative volatilization driving force. As in Figure 2, the test data show a definite pattern of increased degree of decontamination with increases in the soil temperature-time product. Although the data points appear to be gathered a bit more tightly than in Figure 2, data scatter remains considerable. This, again, suggests that parameters other than treatment time and soil temperature are important, or that the dependence on treatment time and soil temperature is not as simple as first order in both.

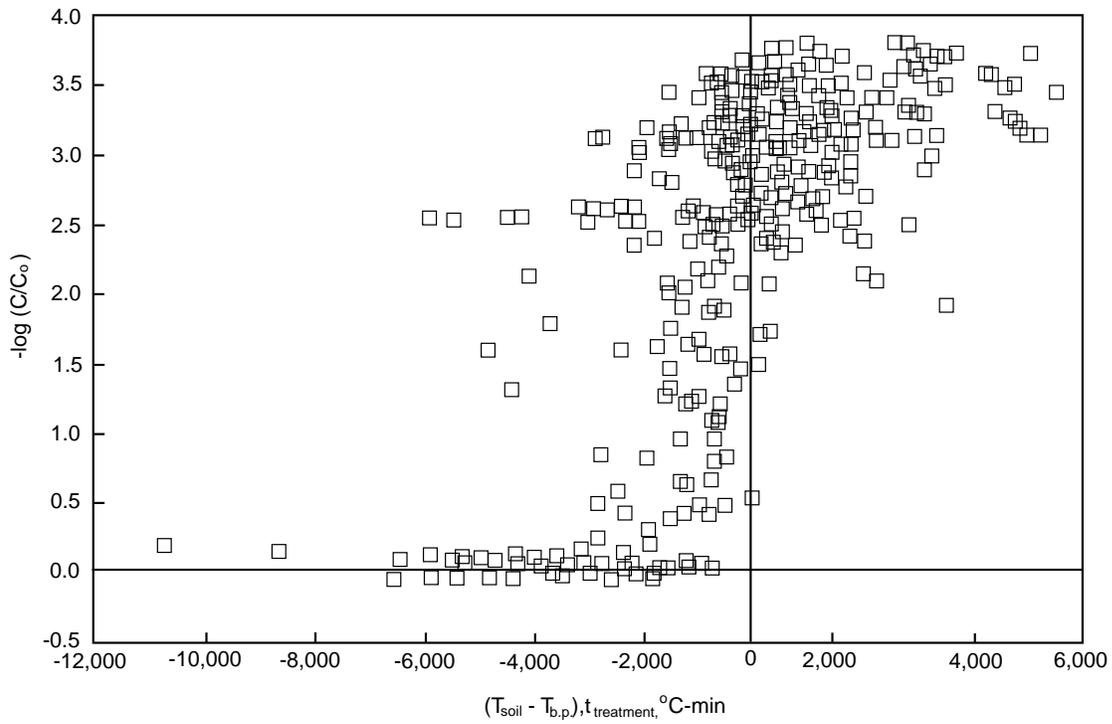
### **Trace Metal Distributions**

Overall average metals mass balance closures achieved in the test program ranged from 96%–113%. Individual metal mass balance closures achieved ranged from 38%–181% at the temperatures tested. On average, arsenic, barium, cadmium, chromium, and lead were not volatile and remained in the soil. With the exception of mercury, the extent of metal volatilization from the treated soil was not significantly affected by any of the test variables. No significant reductions in the fractions recovered in the treated soil occurred with increased treatment time.

Mercury was the volatile metal, as expected, tending to be equally distributed between the treated soil and the scrubber exit flue gas. At the highest soil treatment temperature tested, the extent of mercury volatilization increased with increasing treatment time.



**Figure 2.** Organic compound decontamination effectiveness versus the differences in soil bed temperature and compound boiling point.



**Figure 3.** Effect of cumulative treatment time and achieved solid temperature (adjusted for compound boiling point) on organic decontamination.

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### **Trace Metal Leachability**

The effects of thermal treatment on metals leachabilities in the TCLP varied from metal to metal. Among the test variables, the most influential one was treatment temperature. The behavior of the metals' leachabilities are summarized in the following:

Lead and barium leachabilities were not affected by any of the test variables.

Leachable fractions of arsenic from the untreated soil ranged from 16%–37%, with an average of 26% over the 12 tests. Arsenic leachabilities in the TCLP did not change significantly at low treatment temperatures (soil temperatures below 123°C [254°F]). At maximum soil temperatures ranging from 228° to 277°C (443° to 531°F), arsenic leachability decreased to about 15%. At yet higher soil temperatures (400° to 451°C [753° to 844°F]), arsenic leachability decreased further, to about 10%.

While effects of feed rate and rotation speed were apparent, these effects may be attributable to the different maximum solid temperatures that resulted from the changes in feed rate and rotation speed. Overall, the test data suggest that a minimum soil treatment temperature of 228°C (442°F) is required to reduce arsenic leachability from the synthetic soil tested. Soil

moisture content, within the tested range, had no effect on arsenic leachability.

At the highest soil temperatures reached, above 300°C (572°F), the soil contained a smaller leachable cadmium fraction, at about 2%, compared to about 13%–16% leachable from the feed. It is possible that cadmium leachability in the TCLP may be further reduced at higher soil temperatures.

The chromium in the feed soil was barely leachable, at about 1% or less. The data show that soil temperature affects chromium mobility in the treated soil. A dramatic increase in the leachable fraction of chromium, from less than 1% to more than 15%, was observed when soil treatment temperature was increased from 225°C (437°F) to 275°C (527°F). At higher treatment temperatures and increased kiln rotation rates, the onset of the observed leachability increase occurred at shorter treatment times.

The mercury leachability data suggest behavior comparable to that of chromium. When heated to temperatures of 200° to 275°C (392° to 527°F), the treated soil gave TCLP leachate mercury concentrations two or three times those from the feed samples. These corresponded to leachable fractions of 5%–62%. Unlike chromium, however, when heated above

300°C (572°F), the treated soil TCLP leachate mercury concentrations returned to levels similar to corresponding feed TCLP concentrations.

### **Conclusions**

In summary, operating an incinerator at low-to-moderate temperatures can, under the right conditions, effectively decontaminate soils containing organic contaminants, including high-boiling-point compounds. The principal parameters that affect decontamination effectiveness are compound boiling point, achieved solids temperature, and soil moisture content. Agitation can affect decontamination effectiveness, most likely by increasing the rate at which heat is absorbed into the solid, and by decreasing the average mass transfer resistance.

Except for mercury, trace metal constituents were not volatile under low-to-moderate temperature incineration conditions. The leachability of arsenic, cadmium, and chromium in the TCLP can be affected by treatment temperature.

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**R. C. Thurnau** is the EPA Project Officer (see below).

The complete report consists of two volumes entitled "Evaluation of Rotary Kiln Incinerator Operation at Low to Moderate Temperature Conditions,"

Volume I. Technical Results (Order No. PB96-210414; Cost: \$49.00, subject to change)

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